

Integrated Environmental Assessment for Marine Spatial Planning of Saint Martin's Island, Bangladesh

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Abstract

Marine Spatial Planning (MSP) is widely recognized as a practical approach for implementing Ecosystem-Based Management (EBM) in a sustainable manner. It serves as a valuable tool for coordinating planning efforts among various authorities and institutions. In Bangladesh, MSP has become indispensable for achieving economic growth in a sustainable manner, with a concurrent focus on environmental conservation. An environmental analysis covering 707.39 km² and involving 21 sampling points was conducted in two consecutive years (Winter season of 2021, and 2022) to manage the marine ecosystem of Saint Martin's Island (SMI), which has been under persistent threat. Additionally, a participatory survey was employed to engage stakeholders actively. Principal Component Analysis (PCA) identified water salinity, inorganic nutrients, chlorophyll-a (chl-a), transparency, and pH as the key controlling variables for the ecosystem among the fifteen environmental parameters assessed. The Trophic Status Index (TSI) categorized the environment as good (3.42 to 4.75) within the scale ranging from worst to best (0 to 5). Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) analysis was performed for various objectives, revealing that coral ecosystems, aquaculture, and seaweed fell within the ranges of 89.72 to 99.99, 89.23 to 99.99, and 61.26 to 78.54, respectively, on a scale of 0 to 100. These findings underscore the need for environmental conservation measures to maximize the efficacy of MSP. Furthermore, 70% to 80% of stakeholders advocated for establishing an independent authority to manage SMI, with 65% opposing tourism development. Based on these results, a distinct zone has been proposed, accompanied by specific authorities, to guide the future development and conservation efforts.

Keywords: Marine Spatial Planning; Ecosystem-Based Management; Water Quality Index; Environmental Assessment

1. Introduction

1. As a maritime nation, Bangladesh faces the imperative to manage its critical marine areas in a sustainable and integrated manner. The coastal zone, rich in diverse habitats and ecosystem services that have attracted human activity for centuries, demands effective management to address resource utilization and conflicts (Adger et al., 2018; Brown C & Herkenrath P, 2006). MSP emerges as a vital approach in this context (Lombard et al., 2019).

However, Bangladesh's coastal zones are highly vulnerable to climate change, natural disasters, and anthropogenic disturbances. Swift implementation of regulations for "Ecologically Critical

Areas" (ECAs), exploration of alternative livelihoods for local communities, and additional research are essential for the sustainable exploitation and protection of the unique biodiversity of Bangladesh's sole coral-associated island (Hossain & Islam, 2006).

In the global context, coastal nations have sought effective instruments to optimize the blue economy, with MSP being recognized in approximately 13 countries as a valuable strategy for long-term Ecosystem-Based Management (EBM) (Douvere, 2008; Lombard et al., 2019). MSP, characterized as a holistic planning technique, organizes the use of maritime space, aligning with Bangladesh's goals for planned coastal and marine resource exploitation contributing to the UN Sustainable Development Goals.

Bangladesh's coastline, part of the expansive Bay of Bengal marine ecosystem, teems with diverse species. The blue economy in Bangladesh encompasses artisanal and commercial fishing, shipping, oil and gas exploration, undersea cable installations, shipbreaking, and tourism (Islam & Shamsuddoha, 2018).

The Department of Food and Rural Affairs (DEFRA) defines MSP as "a strategy plan for regulating, maintaining, and safeguarding the marine environment that tackles the various, cumulative, and possibly competing uses of the sea" (Saha & Alam, 2018). MSP, as per UNESCO, is a public process aimed at reviewing and distributing the spatial and temporal distribution of human activities in maritime regions to achieve ecological, economic, and social goals through a political process (Ehler & Douvere, 2007). By addressing multiple, cumulative, and potentially competing uses of the sea, MSP ensures the long-term viability of the marine ecosystem. It is a geographical technique for determining the most suitable areas for various purposes, aiming to avoid and mitigate environmental consequences, facilitate rational marine resource use, and enhance socioeconomic efficiency and ecological security.

Moreover, MSP is a science-based, future-oriented instrument requiring a comprehensive understanding of physical, biogeochemical, and biological patterns and processes, as well as human interactions in the ocean. Anticipating these conditions is crucial to formulating well-thought-out plans for future maritime resource management.

Globally, MSP implementation is still in its early stages (Menegon et al., 2016; E. Olsen et al., 2014). Recently, South Asian countries like India have initiated joint research projects to study the feasibility of MSP in their regions (MoES, 2021; Tailor et al., 2021). Bangladesh is also progressing in this direction, with researchers developing theoretical frameworks and identifying challenges, prospects, opportunities, legal issues, and recommending further developments (Hussain et al., 2017; S. Olsen et al., 2011; Saha & Alam, 2018).

In light of this, the present study focuses on the application of MSP in the context of SMI, Bangladesh. The island's marine ecosystem, facing longstanding threats, necessitates a comprehensive assessment and strategic planning for sustainable development and conservation. The integration of environmental analyses, stakeholder engagement, and the utilization of established indices such as the Trophic Status Index (TSI) and the CCME WQI aims to provide a robust foundation for informed decision-making and policy formulation. Through this research,

we contribute valuable insights to the evolving field of MSP, addressing both global challenges and the specific needs of Bangladesh's marine environment.

2. Materials and Methods

The research is focused on a marine area of 707.39 km² surrounding SMI. Positioned in the northeast of the Bay of Bengal, SMI is approximately 9 km south of the Cox's Bazar-Teknaf peninsular tip and about 8 km west of the northwest coast of Myanmar at the mouth of the Naf River. The island is situated between latitudes 20°34' and 20°39' N and longitudes 92°18' and 92°21' E.

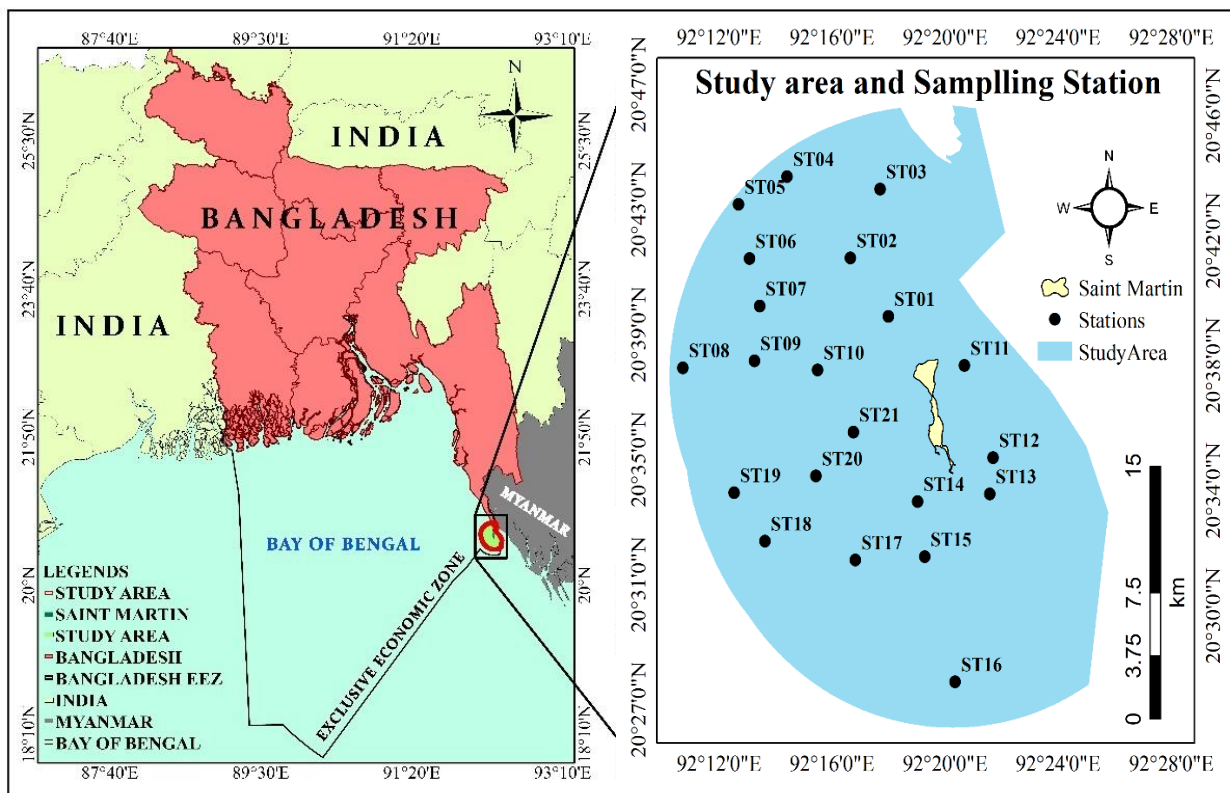


Figure 1: 707.39 km² of study area surrounding St. Martin Island, south-eastern coastal area of Bangladesh.

To fulfill the research objectives, 21 sampling stations were strategically selected, and sampling was conducted during winter and post monsoon in 2022, and 2023. Physicochemical parameters of surface water were measured in situ using a Hanna multimeter (HI98194), Hydro-BIOS CTD, while other parameters were measured in the laboratory. The hack 30038 model single-beam UV-Vis spectrophotometer, employing the powder pillow method, was utilized for the measurement of inorganic nutrients. Inorganic nitrate, phosphate, silica, and ammonia were assessed using powder pillow reagents and following specific methods (Method 8038, 2017; Method 8039, 2019; Method 8048, 2017) Chemical Oxygen Demand (COD) and chl-a were analyzed in the laboratory, employing the USEPA Reactor Digestion Method (HACH, 2021) and (Johan et al., 2014), respectively.

To fulfill the research objectives, water quality was assessed using the Horton model, developed by (Horton, 1965), and the CCME WQI model (Bilgin, 2018). The Trophic Status Index (TSI) was also calculated using the TSI index formula developed by (Fiori et al., 2016; Moon & Kim, 2021; Vollenweider et al., 1998). The analysis was conducted using OriginPro 20, ArcGIS 10.2.5, and SPSS v26, leveraging the resources of the Bangabandhu Sheikh Mujibur Rahman Maritime University, Bangladesh. This comprehensive methodology ensures a robust assessment of the marine environment around SMI, contributing valuable insights to the research objectives.

3. Results

3.1 Physico-chemical Condition of the Area:

Temperature, salinity, pH, and Total Suspended Solid (TSS) stand as pivotal constituents shaping the aquatic environment, determining its fundamental ecosystem status. The outcomes reveal a robust and fundamental correlation among these parameters, showcasing a discernible pattern of temperature variation between the western and eastern sectors of SMI. Notably, the eastern part emerges as distinctly warmer than its western counterpart, extending towards the open ocean, with temperatures ranging from 32.84°C to 27.59°C.

Salinity, a critical metric, exhibits notable variation, reaching its zenith at approximately 33.3 PSU in the south-eastern region and around 32.61 PSU in the western vicinity of the island. In contrast, the lowest salinity is recorded in the northern sector near Bangladesh's primary coast, oscillating between 29.84 PSU and 31.22 PSU. A substantial disparity in COD is observed between the western and eastern peripheries of SMI, with the western region, adjacent to the open ocean, displaying markedly higher COD levels than its south-eastern counterpart near the Myanmar coast. The pinnacle of COD concentration is detected at approximately 2.04 mg/m³ on the island's western side, while the nadir, around 0.64 mg/m³, is noted in the southern region toward the open ocean and the north-western part adjacent to Bangladesh's main coast. Conversely, elevated COD levels, approximately 1.48 mg/m³, persist on the northern side, proximate to Bangladesh's primary coast, extending to the southwestern part facing the open ocean.

TSS and transparency exhibit an inversely proportional relationship. TSS values range between 6 and 10.8 mg/L, peaking near the southern tip of the island (specifically at stations 13, 14, and 17) and registering comparatively lower values at the estuary's entrance. The lowest concentration of TSS is observed at stations 5 to 9. Transparency levels exhibit a spatial dichotomy, with lower values prevailing at the Naf estuary and both the northern and southern extremities of the island (216 to 410 cm), and higher transparency observed towards the open ocean in the west, reaching up to 703 cm.

The distribution patterns for Electrical Conductivity (EC) and Total Dissolved Solids (TDS) demonstrate discernible correlations across the study area. TDS values range from 23 ppt to 25.56 ppt, while EC values span from 46.1 to 51.13 mS/cm. Elevated concentrations of both TDS and EC are discerned in proximity to the island, on both its western and eastern flanks, while lower concentrations prevail in the south-western and north-eastern directions.

3.2. Nutrient Distribution:

The distribution patterns of nitrate and phosphate reveal a parallel trajectory, characterized by a relatively higher concentration of nitrate (ranging from 1 to 1.3 mg/m³) on both flanks of the island. Conversely, elevated levels of phosphate (0.4 to 0.6 mg/m³) are discerned solely in the north-eastern part of the island. Notably, heightened concentrations of both nitrate and phosphate are observed in the vicinity of Teknaf and Cox's Bazaar's coastlines. Towards the open ocean in the south and western directions, lower values prevail for nitrate (0.8 to 0.9 mg/m³) and phosphate (0.03 to 0.3 mg/m³).

The zenith concentration of nitrate, approximately 0.387 mg/m³, is recorded on the south-western side of the island, while the nadir, around 0.105 mg/m³, is noted on the western and eastern sides, facing the open ocean and Myanmar coast, respectively. A notable drop in concentration is observed on the southern side, away from SMI, but proximity to the coast results in a higher concentration of approximately 0.274 mg/m³. Conversely, the highest concentration of phosphate, around 0.19 mg/m³, is found on the southern side, whereas the lowest concentration, approximately 0.054 mg/m³, is registered on the south-eastern side near the Myanmar coast. On the western side, facing the open ocean, and the northern side, adjacent to the main coast of Bangladesh, the concentration drops to around 0.02 mg/m³.

The chl-a concentration fluctuates between 5.36 and 10.50, with the lowest concentrations observed on the northern and south-eastern sides. On the western side, near the coast, the concentration is lowest but progressively increases to around 20.77 towards the Bay of Bengal. In the southern part, Dissolved Oxygen (DO) attains a higher concentration of approximately 7.57 near the coast, slightly decreasing to around 7.22 towards the open ocean. On the northern side, the concentration is around 6.87 near the coast, surges abruptly to 7.91, and then hovers around 7.57 towards the main coast of Bangladesh. Conversely, the lowest DO concentration, approximately 6.18, is recorded in the western part, followed by a dramatic increase to 7.57 towards the open ocean. On the eastern side, a concentration of around 6.87 is noted near the Myanmar coast.

In the nutrient profile, encompassing Silica (SiO₂), Ammonia (NH₃), Nitrate (NO₃), and Phosphate (PO₄), the average phosphate concentration is prevalent across all stations except for stations 6 and 11, registering values of 0.38 and 0.58 ppm, respectively. Unlike phosphate, the other nutrients exhibit more pronounced fluctuations from station to station. Silica demonstrates a decreasing trend from stations 1 to 4, with the highest values recorded in stations 1, 18, and 4 for silica, and ammonia, respectively. In contrast, the lower values for these two parameters are found in stations 9 and 5, respectively.

3.3. Correlation analysis among variables

Temperature, EC, TDS, and salinity exhibit the highest positive correlations with pH, with respective correlation coefficients (r values) of 0.81, 0.63, 0.63, and 0.6. Remarkably, salinity, TDS, and EC demonstrate a robust positive correlation among themselves, denoted by an r value of 1, indicative of a high degree of mutual dependence.

In contrast, COD displays predominantly negative correlations with other parameters, except for a marginal positive correlation with chl-a, silica, Total Suspended Solids (TSS), and Standard

Deviation (SD). DO and ammonia also exhibit primarily negative correlations, albeit with very low r values close to zero. Notably, a negative correlation is evident among silica, ammonia, and phosphate, as well as TSS, with r values of -0.42 and -0.34, respectively. This implies an inverse relationship between these variables.

The correlation analysis elucidates intricate relationships within the dataset, providing insights into the interdependence and potential causal connections among the studied parameters.

3.4. Principal Component Analysis

A PCA was executed to unveil the intricate interrelationships among physico-chemical parameters and nutrient variables. This statistical process aids in visualizing the distribution of the discussed variables and serves to reduce the dimensions of the extensive dataset. The initial assessment of PCA acceptability involved the application of the Kaiser-Meyer-Olkin (KMO) and Bartlett's Test.

The KMO and Bartlett's Test results fall within the range of 0 to 1, indicative of the acceptability of PCA. In this case, the obtained result of 0.517 suggests that the PCA is acceptable under moderate conditions.

3.1.1 Identifying Controlling Physico-chemical Parameters using PCA:

Principal Component 1 (PC1) singularly accounts for 32.37% of the variance among the 15 components, while PC2 contributes 15.84%. Subsequently, PC3, PC4, and PC5 exhibit variances of 12.08%, 10.187%, and 8.33%, respectively. Collectively, these four components elucidate 78.81% of the dataset variance, with the first five components encapsulating 80% of the cumulative percentage. PC1, PC2, and PC3, when combined, explain 60.29% of the information in the main dataset.

In station-wise evaluation, PC1 to PC5 collectively capture around 80% of the cumulative percentage of variance. Station 13 positively contributes to PC1 to PC4, while Station 3 has a negative impact on PC1 to PC4. Specifically, in PC1, Station 13 attains the highest positive score of 1.34, whereas Station 18 records the highest negative score of -1.72. In PC2, Station 11 boasts the highest positive score of 1.87, while Station 19 accrues the highest negative score of -2.04.

The biplot illustrates the contribution of each parameter to individual principal components. Notably, for PC1 vs PC2, Density, Salinity, EC, and TDS make significant positive contributions to PC1, while Chl-a, Nitrate, Temperature, and pH wield a substantial impact on PC2 in a positive manner. Concurrently, DO exhibits a negative contribution. Additionally, Ammonia, TDS, and Phosphate exert positive influences on PC3, counteracted by a negative impact from DO. This biplot provides a comprehensive visualization of the intricate relationships among the variables, shedding light on their collective contributions to the principal components.

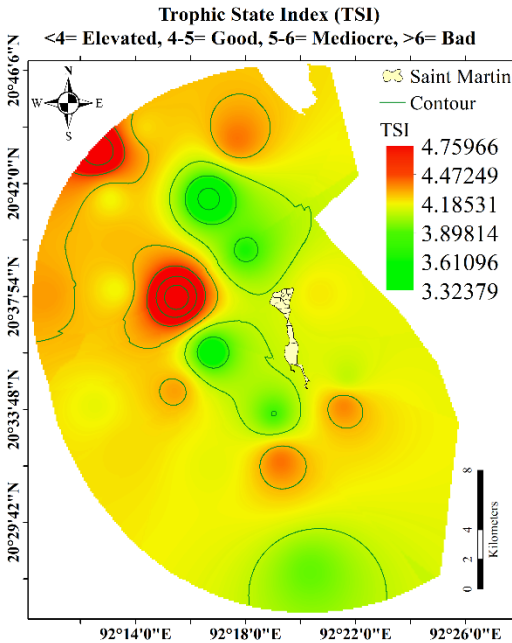
3.5. Present Environmental Condition

3.5.1. Trophic Status Index

The Trophic State Index (TSI) serves as a method to assess the health status and trophic condition of an ecosystem. The TRIX method employs four parameters, as per the equation developed by (Vollenweider et al., 1998), to calculate the TSI.

$$TRIX = \frac{10}{12} ((\text{Log}M_{chl-a} + 0.5) + (\text{Log}M_{DO} + 1) + (\text{Log}M_{TIN} - 0.5) + (\text{Log}M_{TP} + 0.5))$$

$$\text{Or } TRIX = \frac{1}{1.2} (\text{Log}(M_{chl-a}M_{DO}M_{TIN}M_{TP}) + 1.5)$$



TSIs for Chl-a, Total Phosphate (TP), Total Inorganic Nitrate (TNI), and Secchi Depth (SD) of the reservoir were determined using the methodology proposed by Carlson (Carlson, 1977). The calculation involved obtaining the arithmetic average of the three individual TSIs, resulting in Carlson's Trophic State Index (TSIC). One of the advantages of TSI is its ability to represent trophic conditions on a continuous quantitative scale. Oligotrophic waters exhibit a TSI of less than 40, mesotrophic waters fall within the range of 40 to 50, eutrophic waters display a TSI of 50 to 70, and hypereutrophic waters have a TSI exceeding 70 (Kratzer & Brezonik, 1981; SIMONS et al., 1996). Additionally, TSITN was calculated using the method outlined in the literature (Kratzer & Brezonik, 1981).

Figure-2: Distribution plot of trophic status index result over SMI.

3.5.2. Coral Ecosystem WQI

The standard or optimum requirements for parameters in the coral reef ecosystem are as follows: Temperature (29.6 to 21.7°C) (Locarnini et al., 2010), pH not less than 7.3 (Guan et al., 2015), EC (mS/cm), TDS (ppt), and Salinity (PSU) should range from 30 to 60 (Dupont, 2020; Pal et al., 2015), 30 to 40 (S. Moran, 2018), and 28.7 to 40.4 (Antonov et al., 2010), respectively. Additionally, TSS, PO₄, NO₃, and NH₃ (ppm) should be below 20 (Manoppo et al., 2014), 2.7155 (Garcia et al., 2018), 19.43 (Garcia et al., 2018), and 0.1 (Zhu et al., 2004), respectively. The optimum levels for DO are between 5 to 8 ppm (*Dissolved Oxygen - Environmental Measurement Systems*, n.d.), and transparency should be at least 300 cm (Yentsch et al., 2002).

To assess suitability, the entire study area was divided into six regions. Region A. Using these standardized data, the CCME WQI was calculated. The result is depicted in Figure 3, representing suitable zones for coral growth based on existing water quality.

This suggests that the overall study area is conducive to coral-associated ecosystems, at least during the winter period. It's important to note that these findings may not apply to other seasons due to insufficient data. Among these zones, red indicates higher suitability than blue. The north-

western part is more suitable than the south-western part, and greater depth appears comparatively less suitable for the coral ecosystem.

3.5.3. Aquaculture Potential in the Region and its Correlation with Coral Habitats

In this context, aquaculture encompasses the cultivation of mussels, other shellfish, and/or polychaeta reefs, seagrass, etc., which naturally thrive in this region (Locarnini et al., 2010). Given the region's proximity to the mainland, ample depth, reduced susceptibility to natural hazards, and the traditional reliance of local communities on fishing, the introduction of marine aquaculture and case culture emerges as a novel strategy aligned with Sustainable Development Goal 14 (SDG-14).

For optimal aquaculture growth, certain physico-chemical parameters must adhere to standard values. Chl-a levels ($\mu\text{g/L}$) should fall within the range of 3.97 to 52.51 (Gernez et al., 2017). Temperature ($^{\circ}\text{C}$) is recommended to be maintained between 23 to 32 (Lucy, 2015). Additionally, pH, EC in mS/cm , salinity in PSU, nitrate and ammonia levels in ppm, and DO in ppm should be within the ranges of 7.5 to 8.5, 50 to 60, 25 to 40, >100 , 0 to 0.5, and <4 , respectively (Biomin, 2020). TDS in ppt, Phosphate (PO_4) in ppm, and Silicon Dioxide (SiO_2) in ppm should range from 30 to 40, >2.7155 , and 0.04 to 8, respectively (Dupont, 2020; Garcia et al., 2018; S. Moran, 2018).

A noteworthy observation is the striking similarity between coral-suitable sites and areas conducive to aquaculture. This correlation is unsurprising given that the most robust fisheries thrive in proximity to coral ecosystems, known for supporting exceptionally diverse biodiversity.

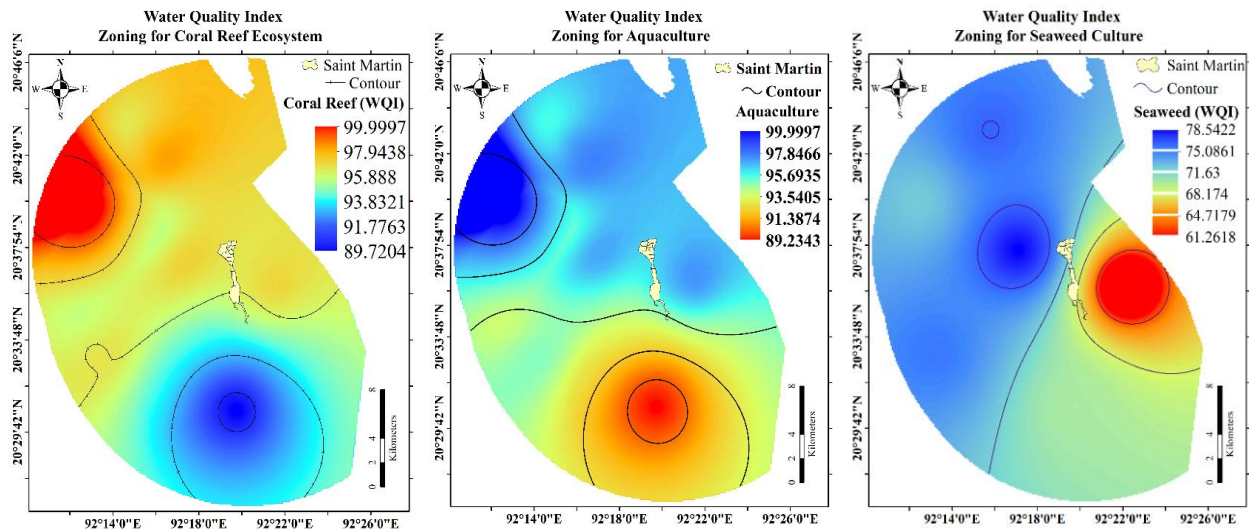


Figure-3: Distribution plot of water quality index for Coral Reef Ecosystem (left), Aquaculture (center), and Seaweed Cultivation (right) over SMI.

The pattern observed in this figure mirrors the coral ecosystem, and considering the bathymetric profile, we infer that the western part is more favorable than the eastern part. Notably, areas with relatively higher freshwater content appear to be more suitable, indicating a potential correlation between water salinity and aquaculture viability.

3.5.4. The Significance of Seaweed Cultivation in Bangladesh's Blue Economy

Seaweed, a marine plant, thrives in tropical and subtropical regions along coastlines worldwide (N. Ahmed & Taparhudee, 2005). Since ancient times, seaweeds have served as a valuable source of nutrients, food, fertilizer, and medicine (Lavanya et al., 2017; Salehi et al., 2019). Over time, their utility expanded into industrial applications such as gas and fertilizer production, potash sourcing, iodine extraction, and hydrocolloid extraction (Tziveleka et al., 2019; Zaremba & Smoleński, 2000). The global cultivation of seaweed has more than doubled in the past decade, reaching 30.4 million tons in 2015 from 14.7 million tons in 2005. Leading the production charge are countries such as Chile, China, Norway, Indonesia, and South Korea (Ferdouse et al., 2018). Globally, more than 221 seaweed species are utilized, with 145 for food and 101 for hydrocolloid extraction (Zaremba & Smoleński, 2000).

In the context of Bangladesh, the blue economy presents a diverse range of opportunities, and seaweed aquaculture stands out as a significant prospect. The country boasts a natural shoreline extending 120 km, characterized by a wide, gentle slope that is conducive to seaweed cultivation and possesses suitable physiochemical parameters (Buschmann et al., 2017). Additionally, seaweeds play a crucial role in mitigating global warming by absorbing substantial amounts of CO₂ from the atmosphere. Therefore, considering both economic and environmental factors, the Bangladeshi shoreline offers a potential site for large-scale seaweed cultivation (Krumhansl et al., 2016).

For successful seaweed cultivation in Bangladesh, certain environmental conditions must be met. These include avoiding bloom conditions for Chl-a, TSS levels below 10 ppt, and transparency above 300 cm (Jamaluddin et al., 2019). Recommended temperature (24 to 28°C), pH (7.5 to 8.5), salinity (24 to 37 psu), dissolved oxygen (6.1 to 7 ppm), and depth within 3 to 15 meters have been suggested for the Bangladeshi coast (Zafar, 2005, 2007). Optimal EC ranges from 30 to 60 mS/cm (Dupont, 2020; Pal et al., 2015), and TDS should be maintained between 30 to 40 ppt (S. Moran, 2018). Additionally, recommended values for COD are below 1300 ppm, phosphate (PO₄) less than 0.17 ppm, and nitrate (NO₃) at 0.34 ppm for seaweed culture (Hoq & Hasan, 2017; Yuniati Santi, Syah, T.Y.R., Darmansyah, 2017).

Seaweed culture site suitability analysis reveals an interesting scenario, presenting a complete opposite between the eastern and western parts of the island. As depicted in Figure-3, the eastern part is more suitable than the western part, with suitability scores ranging from 61 to 78 on a scale of 100 to 0 (representing the best to poor sites). While the Water Quality Index (WQI) suggests that the study area may not be highly suitable for seaweed farming, it remains plausible with preventive measures and careful considerations for optimal results.

3.5.5. Comprehensive Assessment of Overall Water Quality Index in the Region:

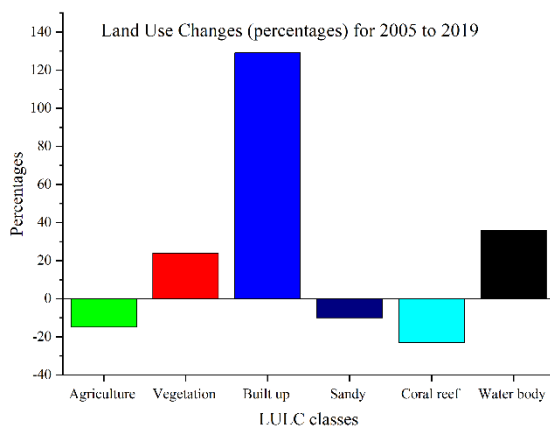
The assessment of environmental health conditions has been meticulously conducted and analyzed through the application of the CCME method, an acronym denoting the Canadian Council of Ministers of the Environment. The results, presented in Table-4, showcase the calculated Water Quality Index (WQI) for each individual region. A thorough examination of Table-4 reveals that Region B stands out as relatively more favorable for both coral ecosystems and aquaculture,

exhibiting commendable values for seaweed cultivation. In contrast, Region D displays inadequacy for seaweed culture, while Region F falls short in supporting aquaculture endeavors. However, the remaining regions exhibit overall good and acceptable conditions for the coexistence of coral ecosystems, aquaculture, and seaweed cultivation. This detailed analysis provides a nuanced understanding of the water quality dynamics across the diverse regions under scrutiny.

3.6. Land Use and Land cover Change (LULC)

3.6.1. Land Use Dynamics Over the Last 15 Years on SMI:

A comprehensive examination of the land use patterns on SMI over the past 15 years reveals significant transformations. Noteworthy changes have occurred in the extent of various land uses, with some experiencing expansion while others have contracted.



Positive Changes in Land Use:

Among all land uses, the most substantial increase in area coverage has been observed in the category of Buildup area. This specific land use has witnessed a remarkable surge, registering a staggering 120% growth between 2005 and 2019. Additionally, positive changes of 42% and 23% have been recorded for inland water bodies and natural vegetation, respectively.

Figure- 4: Land use land cover change percentage for 2005 to 2019.

Negative Changes in Land Use:

Conversely, a comprehensive analysis indicates an overall decrease in the coverage of coral reefs, agriculture, and sandy beaches by 25%, 17%, and 12%, respectively, over the specified period. These reductions signify a shift in the landscape dynamics, prompting a closer examination of the implications for ecological balance and sustainable land management on SMI.

This detailed overview provides valuable insights into the dynamic interplay of human activities and natural features, shaping the evolving landscape of SMI.

3.6.2. Human Settlements and Hotel Distribution Analysis:

The distribution of built houses and hotels for tourists on SMI has been meticulously examined based on primary field study data. The study area was systematically divided into 12 regional zones, and an Inverse Distance Weighting (IDW) method was employed to create a distribution

map. The findings underscore a discernible pattern of human settlement and hotel development across the island.

Regional Segmentation and Population Density:

The northern part of SMI emerges as the most densely populated, with a concentration of tourist hotels. Further segmentation into four zones within the northern part reveals distinct variations. The north-eastern section, proximate to the bazaar, exhibits the highest density of houses, while the western beach area follows closely in terms of population density. Interestingly, the distribution of hotels contrasts with that of houses in the same zones, indicating strategic variations in land use planning.

Spatial Dynamics and Infrastructure Impact:

Between the western beach and north-eastern part, a less densely built area is observed. This phenomenon can be attributed to the presence of a large inland water body and the passage of the city sewage line through this region. The Golachipa region and the southernmost part of the island show lower housing density, while the area between Golachipa and Chera Dwip exhibits fewer human settlements and a limited number of hotels. Notably, this zone features higher proportions of agricultural and vegetated land.

Land Use and Cover Change:

Figure-4 illustrates the percentage change in land use and land cover from 2005 to 2019, providing a visual representation of the dynamic alterations in the landscape over the specified period. This comprehensive analysis sheds light on the intricate interplay between human activities, infrastructure development, and the evolving environmental footprint on SMI.

3.7. Stakeholder's Recommendation

From planning to execution, the active participation of stakeholders is crucial in all stages. The primary aim of MSP is to achieve social development by maximizing economic benefits while concurrently conserving a healthy ecosystem. In the case of SMI's MSP, key stakeholders include local residents, fishermen, and other local resource users, and ensuring their involvement is imperative. To address sustainable ecotourism on SMI, a survey targeting secondary stakeholders was conducted as part of this study. The survey results are outlined below.

A total of 530 participants took part in the survey, distributed across three age groups: 18% below 25, 8% above 35, and the majority, 74%, falling between 25 and 35 years of age. Educational status was categorized into four groups, with 73% completing undergraduate studies, 8% holding master's degrees, 3% having education beyond master's, and 16% completing HSC.

Regarding environmental concerns, over 65% of participants expressed agreement with the notion that uncontrolled tourism contributes to environmental degradation. On average, more than 85% of all participants identified key reasons for the current state of tourism, citing tourist unawareness, mismanagement by government institutions, local community unawareness, and the lack of coordination among responsible organizations and institutions.

In terms of satisfaction, 52% and 66% of participants strongly expressed dissatisfaction with present tourism zoning facilities and visitors' ocean literacy, respectively. Additionally, approximately 56%, 63%, and 65% of participants strongly agreed on the need for integrated management, improved ticketing facilities, and enhanced government willingness for better tourism, respectively.

4. Discussion

Upon meticulous analysis encompassing field data, laboratory investigations, and observations, a comprehensive outcome emerges. Addressing all pertinent issues, including social aspects, environmental concerns, and economic considerations, the necessity for a holistic management plan is evident. The MSP emerges as an invaluable tool, aligning with the primary objective of this research. Subsequently, a detailed marine spatial plan has been formulated for SMI.

This proposed plan for SMI delineates spatial arrangements for both the marine and inland components. The marine sector encompasses fishing, aquaculture, seaweed farming, boat anchoring, a marine sanctuary, general-use zones, shipping routes, and cable connections. Figure-3 illustrate the water quality for coral ecosystems, aquaculture, and seaweed farming, respectively. The proposed MSP plan considers standard values, bottom topography, and bathymetry.

Five distinct zoning proposals are outlined in the proposed plan. The green zone in the western and north-western directions signifies the zone for marine aquaculture. Adjacent to SMI on the western side, the blue-shaded zone is designated for seaweed farming, accounting for prerequisites such as transparency, salinity, nutrient availability, and bottom topography. The purple-shaded zone in the north, north-west, and south-east represents marine fishing sites under regulatory measures. In overlapping zones, further study is required to determine the best output and potential seasonal alterations.

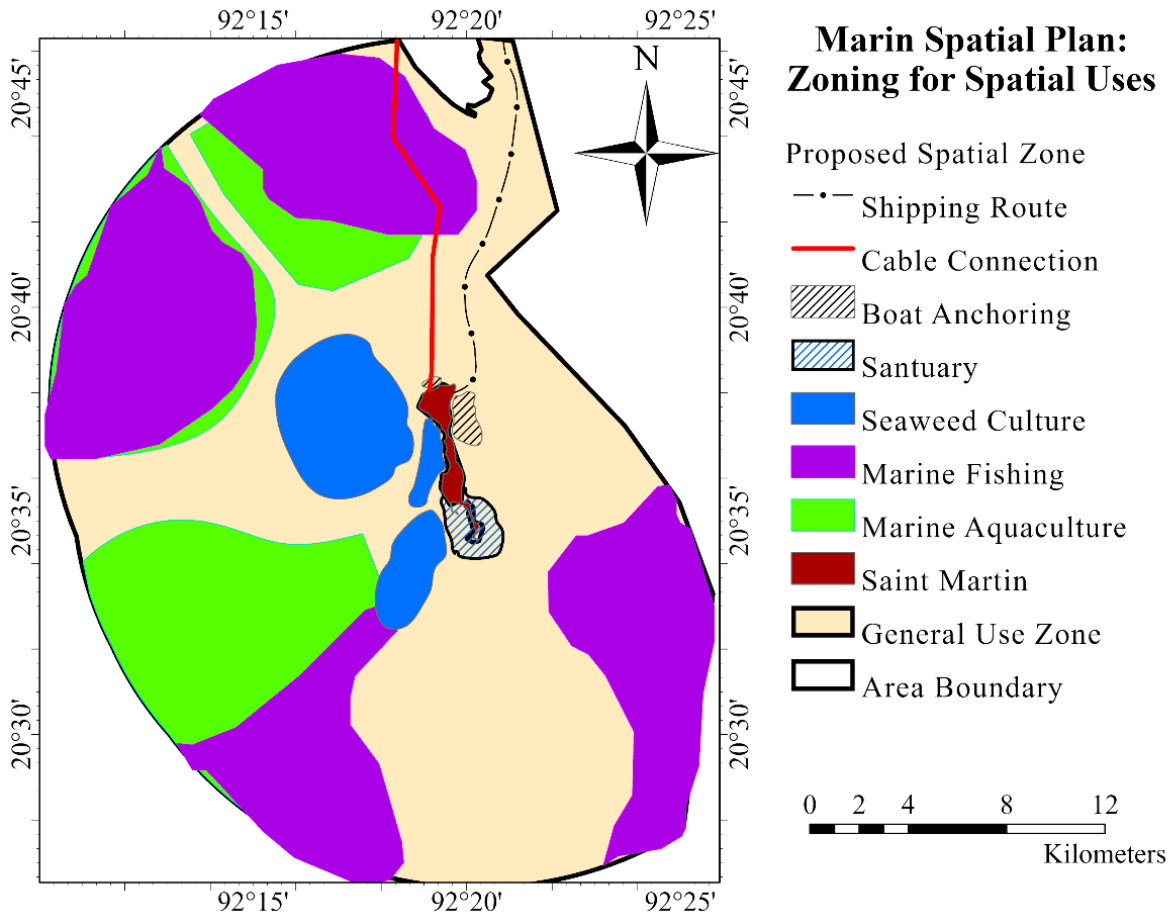


Figure- 5: Proposed Marine Spatial Plan for Saint Martin Island, Bangladesh.

A proposal for a marine sanctuary in the southern part of the island, named Narikal Zinjira, aligns with its existing designation by MoFEC (Tomascik, 1997). The traditional practice of boat anchoring around the island, while harming ecological health, prompts a proposed boat anchoring zone in the jetty area. The bottom features of easy accessibility and beach inclination support boat anchoring facilities, depicted by line features in the plan. A dotted line represents the current shipping route, facilitating communication with the mainland. To provide electricity, telecommunication lines, and internet services on the island, a proposed submarine cable connection route from the western bank of the island to Teknaf is suggested.

SMI is home to approximately 8000 permanent residents, the majority of whom are fishermen (Md. Shahjahan, 2005). Over 5000 people directly or indirectly rely on fishing for their livelihood

on this small island (M. K. Ahmed et al., 2021). Additionally, hotel businesses, agriculture, and local grocery enterprises constitute the primary professions on the island.

The identification of conflicts is a crucial step in achieving the best outcomes in the MSP process. However, before identifying conflicts, it is essential to recognize stakeholders, as conflicts often arise among resource users. To ensure a successful MSP, two distinct spatial plans are required: one exclusively for marine areas and the other for the island. The initial task before planning is to identify stakeholders directly or indirectly related to this project within the study area. Stakeholders are conventionally categorized as primary and secondary stakeholders, each with various degrees of direct or indirect involvement. Additionally, a party with vested interests may attempt to create barriers before any project initiation. A regulatory authority is essential before commencing any working activity or project. Given the multidisciplinary nature of MSP, involving individuals from diverse fields with varied experiences is necessary. MSP, being a complex task, can be divided into two major parts: authority for planning MSP and authority for implementing MSP.

Both types of authority hold equal importance. While they could be combined into one organization, many MSP initiatives worldwide establish a new authority for MSP planning, with implementation carried out through existing authorities and institutions. In the context of Bangladesh, several government institutions and authorities have already been established for forest conservation and management, as well as experience in managing marine protected areas. Therefore, the Ministry of Forest and Climate Change could be considered as one of the choices for implementing MSP for SMI. Additionally, establishing a new authority for planning and feasibility analysis, involving individuals with diverse sectoral experiences, would be beneficial. Typically, projects on public demand are funded by government funds. However, for this project, international donor organizations should be the primary target, followed by public-private partnerships as the second option.

Several foreign donor agencies, with prior involvement in projects in Bangladesh and other MSP projects globally, present viable options. These agencies include UNDP, USAID, UKAID, the World Bank, JICA, ADB, etc. Alternatively, exploring public-private partnerships within the country or internationally is another avenue. While Bangladesh lacks direct experience in implementing MSP, involving individuals with foreign experience, directly or indirectly, is crucial for national projects.

Bangladesh is likely to face a data crisis as historical long-term environmental, climatological, and demographic data for its coastal region have been scarce. Implementing an ecosystem-based working approach requires long-term observation and assessment before initiating the project to achieve sustainable and efficient results. A thorough study over 5 to 10 years in a specific region for a specific purpose is crucial to understanding the ecosystem and its mechanisms. For a successful MSP plan, the collection and proper analysis of all types of social, scientific, and economic data are necessary for the best strategic plan.

5. Conclusions

The distribution of the majority of parameters exhibited a consistent pattern, delineating the study region into three zones: upper (north-eastern), center (east and west sides of SMI), and lower (south-western). With the exception of COD, SD, DO, and NH₃, the south-eastern coast of SMI demonstrated the highest concentration for most variables. Dissolved inorganic nutrients, particularly silica, exhibited a scattered distribution. Chl-a and DO concentrations ranged from 10.49 to 25.90 mg/L in the eastern side of SMI and 6.5 to 7.57 mg/L in the upper and lower zones, respectively. Stations 6 and 11 deviated from the average phosphate concentrations, registering 0.38 and 0.58 ppm, respectively. Nutrient levels, excluding phosphate, showcased considerable variability across stations.

Temperature, EC, TDS, and salinity exhibited the strongest positive correlation with pH, with respective correlation coefficients of 0.81, 0.63, 0.63, and 0.6. Salinity, TDS, and EC demonstrated a perfect positive correlation ($r = 1$) among themselves. COD demonstrated predominantly negative correlations, except for a slight positive correlation with chl-a. Silica, TSS, SD, DO, and NH₃ displayed mostly negative associations, with occasional low positive correlations with chl-a. The highest negative correlation was observed between SiO₂, NH₃, and PO₄, and TSS, with respective correlation coefficients of -0.42 and -0.34.

The Trophic State Index (TSI) for the entire research region fell within the range of 3.32 to 4.75, indicating a moderate environmental health condition. Among the six regions, the best TSI was observed in region A, while region C exhibited lower or moderate TSI. The overall Water Quality Index (WQI) for coral ecosystems, aquaculture, and seaweed farming, calculated using the CCME method, yielded excellent scores for coral ecosystems and aquaculture, but moderate or suboptimal scores for seaweed culture. The scores for the three categories ranged from 89.72 to 99.99, 89.23 to 99.99, and 61.26 to 78.54, respectively. This suggests the need for environmental conservation measures to maximize the outcomes of MSP.

The Pearson correlation coefficient analysis of individual parameters on coral ecosystem health, aquaculture, and seaweed farming suitability in SMI revealed moderate correlations for SD (0.43), NO₃ (-0.53), SiO₂ (-0.69), while other parameters exhibited weaker correlations.

In the final proposal of the research, the study area is suggested to be divided into three economic zones (coral reef fisheries, marine aquaculture, and seaweed farming), two special use zones (marine sanctuary and boat anchoring), and one general use zone based on major economic activities, public demand, available resources, facilities, and analysis findings. Adherence to all guiding principles of MSP is essential for achieving optimal economic, social, and environmental benefits.

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